US009645035B1

(54) **IMPARTING MOTION TO A TEST OBJECT SUCH AS A MOTOR VEHICLE IN A CONTROLLED FASHION WITH IMPROVED ACCURACY**

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    G01L 1/00   (2006.01)
(52) **U.S. Cl.**
    CPC *G01L 25/00* (2013.01); *G01L 1/00* (2013.01)

(58) **Field of Classification Search**
    USPC 73/117.01, 117.02, 117.03, 146, 669, 670
    See application file for complete search history.

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(57) **ABSTRACT**

An apparatus imparts motion to a test object such as a motor vehicle in a controlled fashion. A base has mounted on it a linear electromagnetic motor having a first end and a second end, the first end being connected to the base. A pneumatic cylinder and piston combination have a first end and a second end, the first end connected to the base so that the pneumatic cylinder and piston combination is generally parallel with the linear electromagnetic motor. The second ends of the linear electromagnetic motor and pneumatic cylinder and piston combination being commonly linked to a mount for the test object. A control system for the linear electromagnetic motor and pneumatic cylinder and piston combination drives the pneumatic cylinder and piston combination to support a substantial static load of the test object and the linear electromagnetic motor to impart controlled motion to the test object.

5 Claims, 13 Drawing Sheets
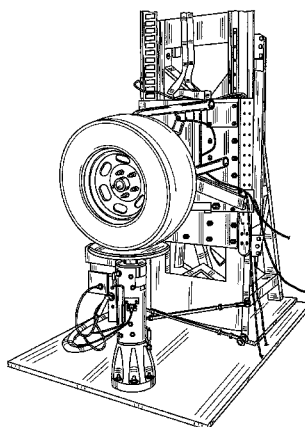
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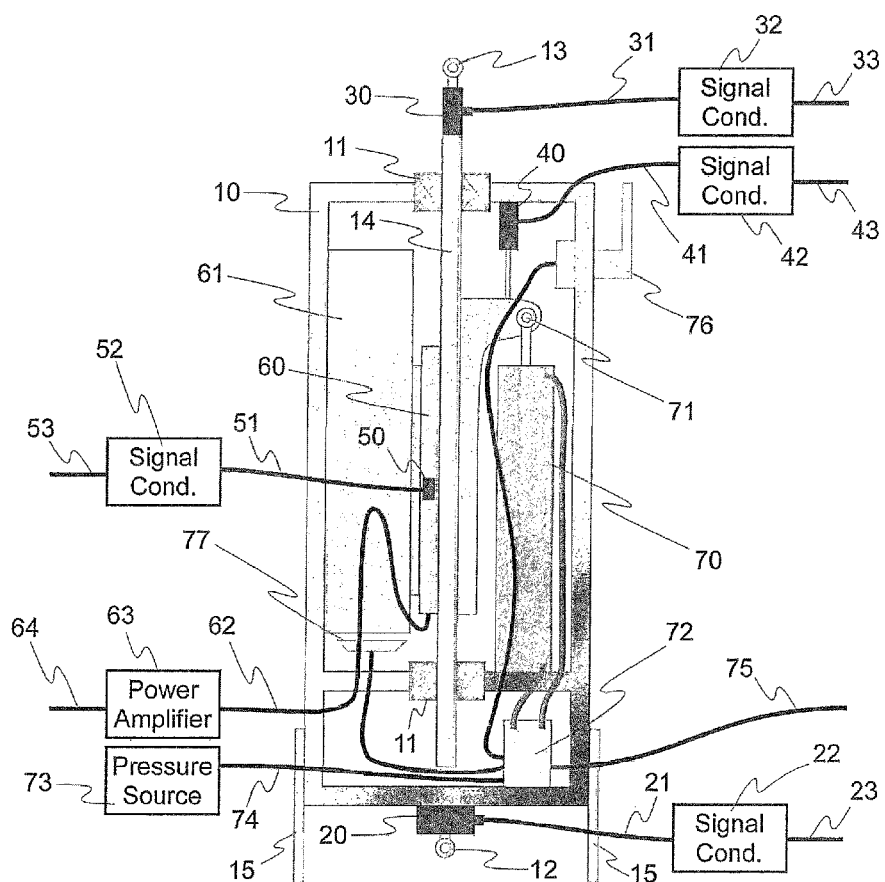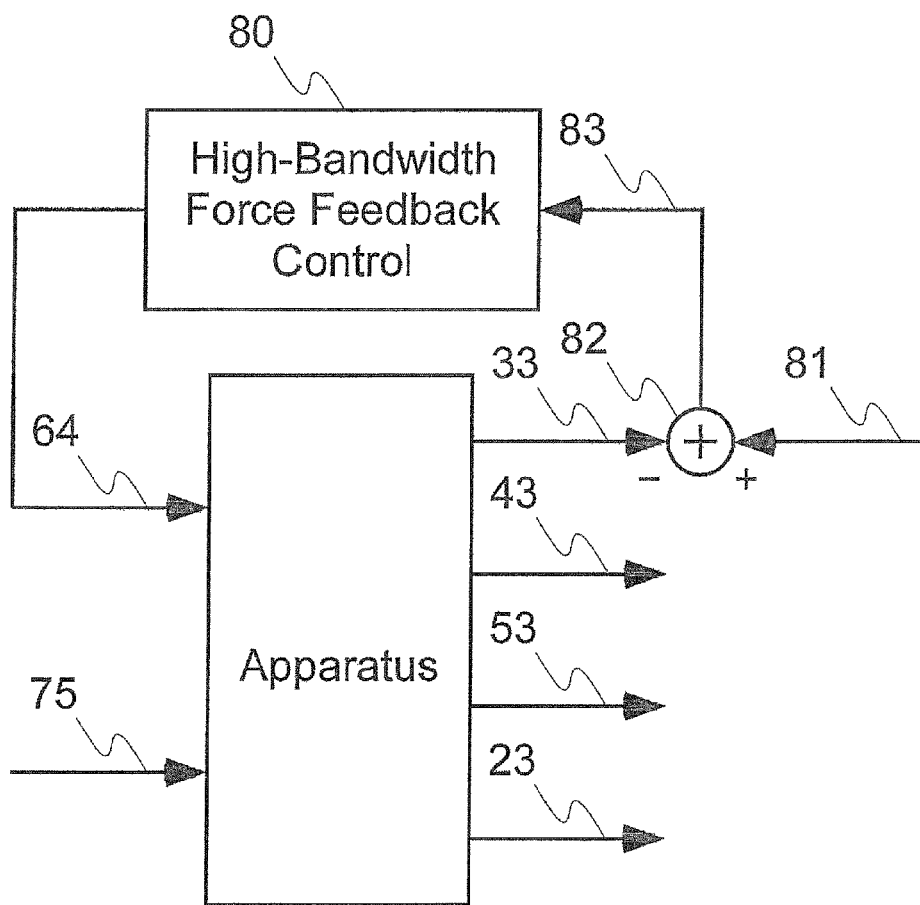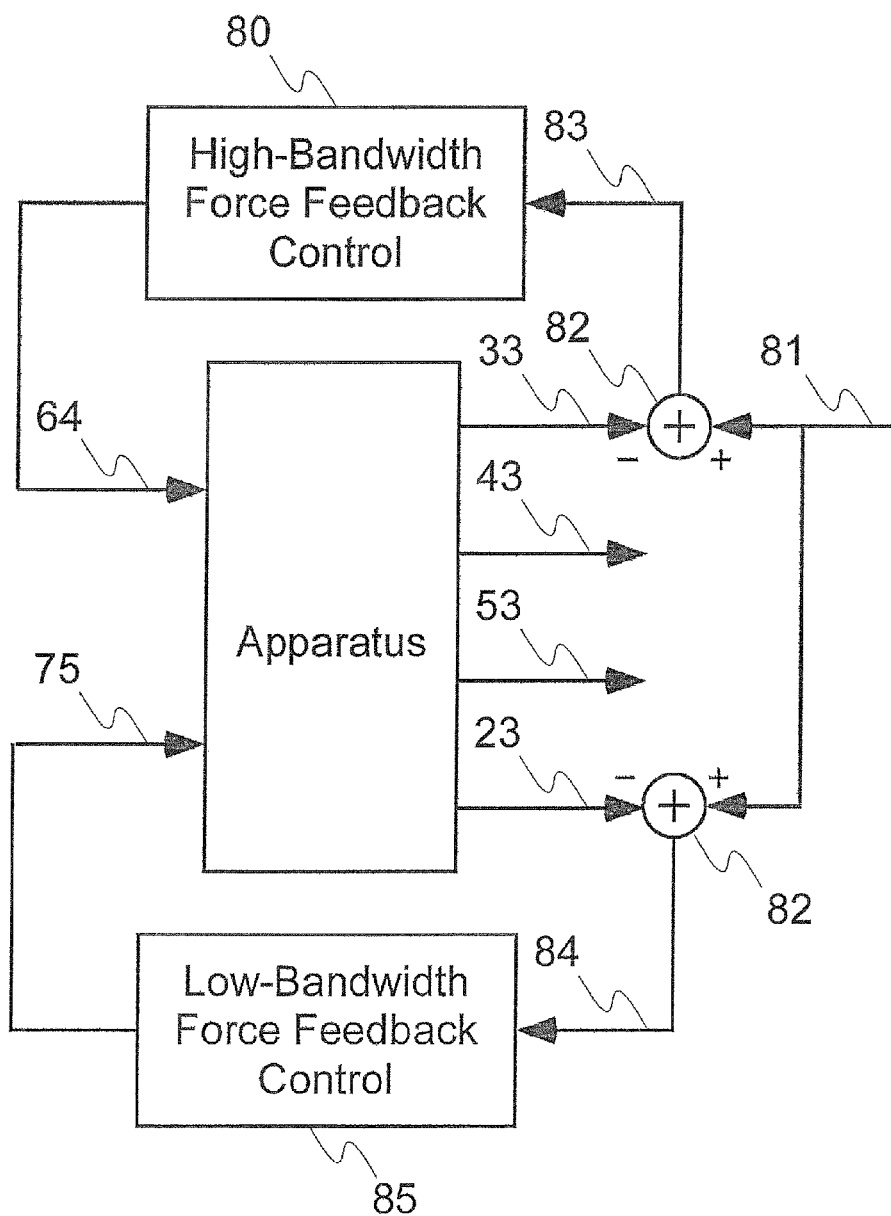
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Figure 1

80

High-Bandwidth
Force Feedback
Control

83

33 82 81

64

− +

Apparatus 43

53

75 23

Figure 2

Figure 3

80

High-Bandwidth
Force Feedback
Control

83

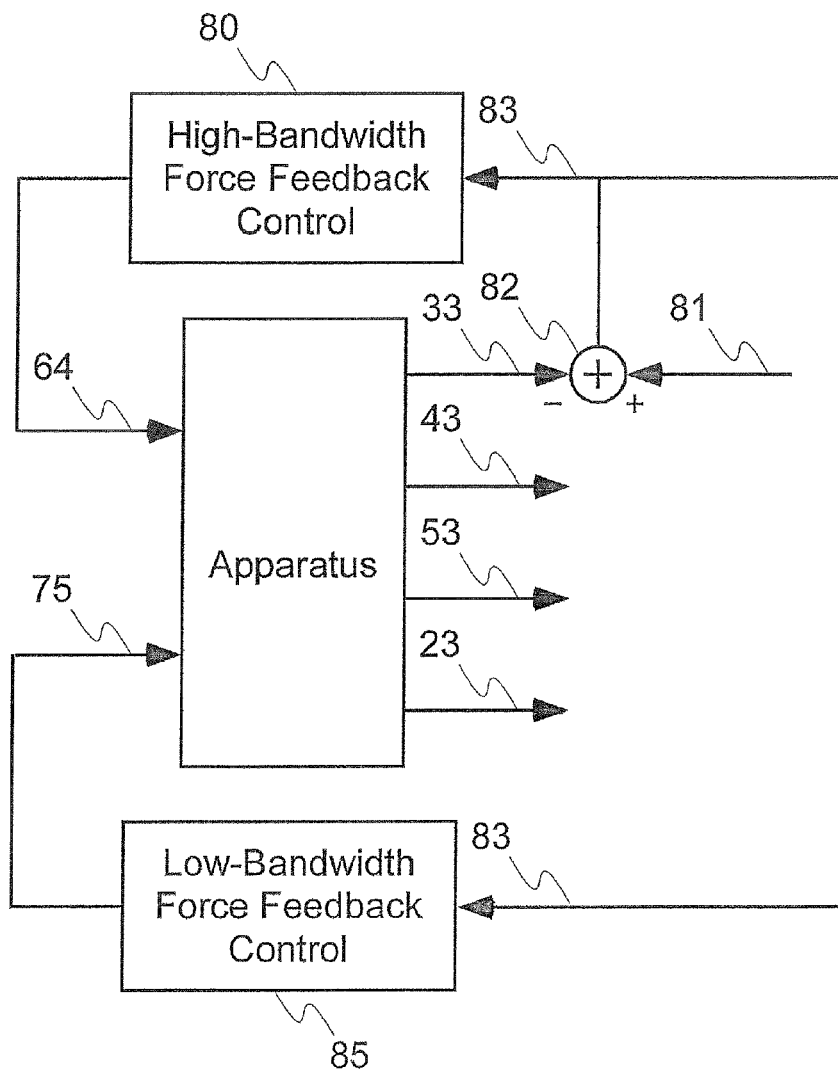33　82　81

64

75

Apparatus
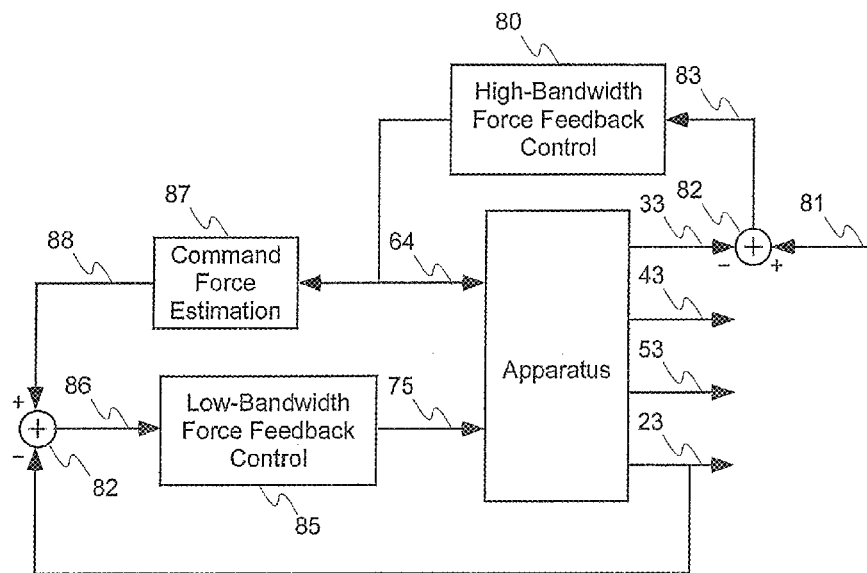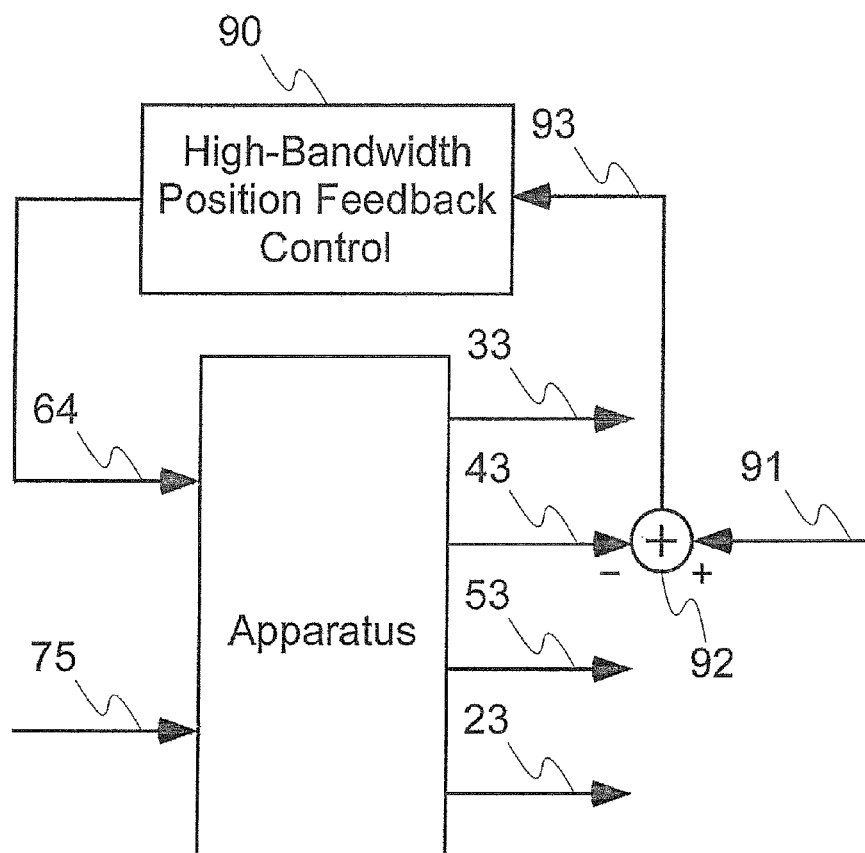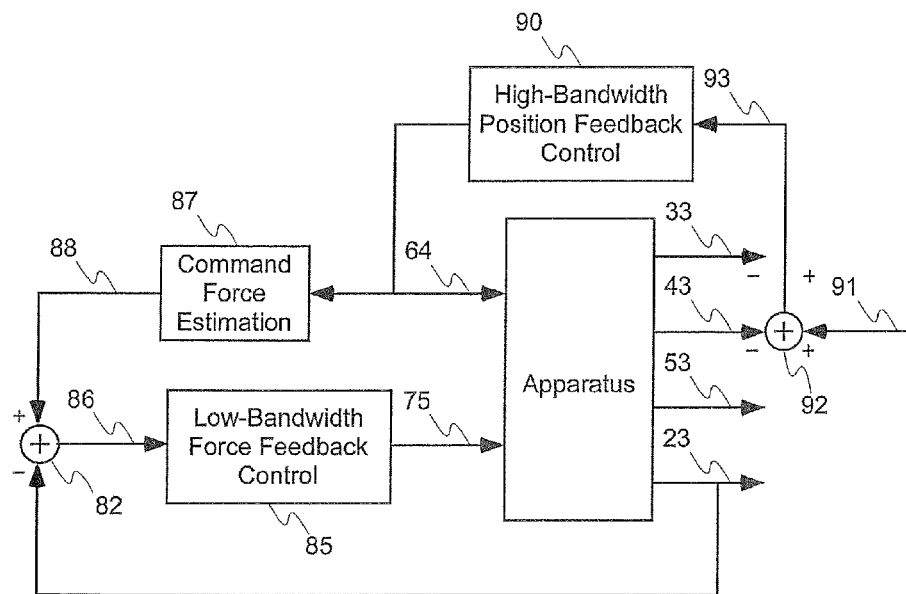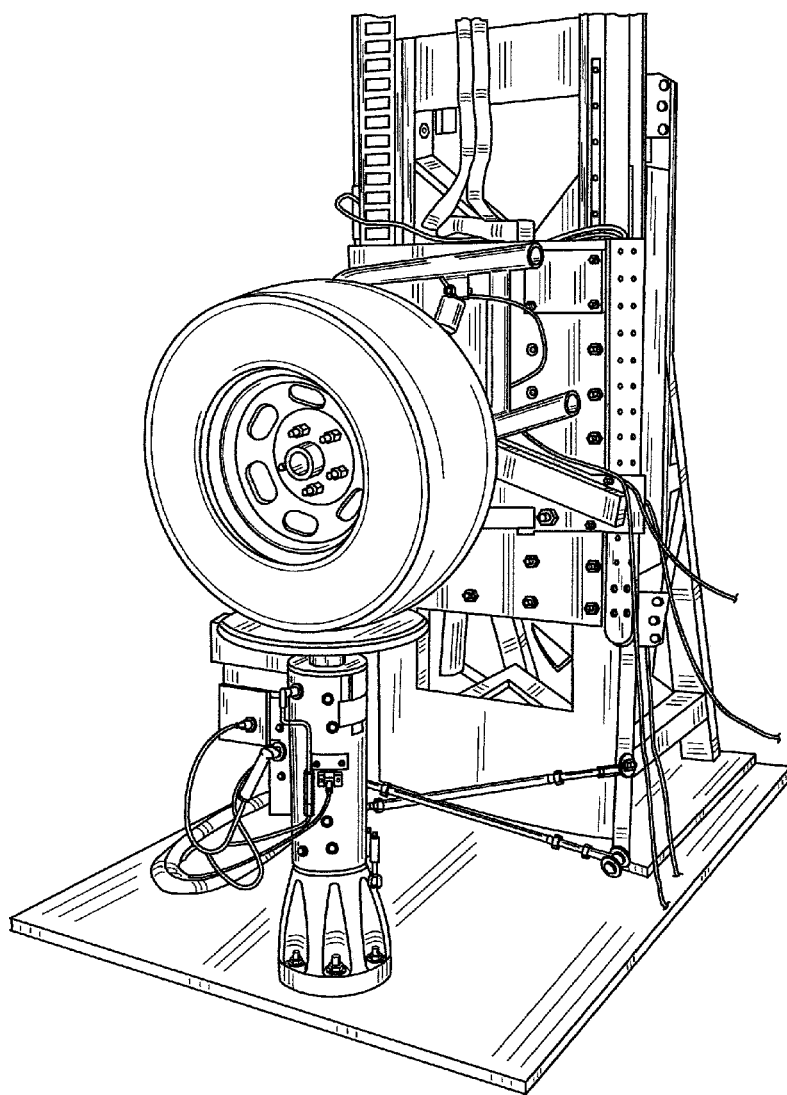
43

53

23

Low-Bandwidth
Force Feedback
Control

83

85

Figure 4

Figure 5

Figure 6

Figure 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

SCHMERSAL SAFTY CONTACTS — 138

NSERVO FUNCTIONALITY — 134

DIG OUT nSERVO DO4 Compression

DIG OUT nSERVO DO5 Tension — 136

DIG OUT nSERVO DO6 ENABLE — 140

Logic Comparator >0 YES NO — 132

Absolute Value ABS — 126

J106PS.10 AOUT0 0-10V — 128

122

124

MOVING AVG FILTER (set in Shock s/w) — 125

DC Bias -10 to 10V (set in Shock s/w)

AIN +-5V — 120

L/C Signal Conditioner REI Electronics Board — 118

116

Voltage-Controlled Pressure Regulator E2223-043H

PRESSURE IN 150 PSI MAX

Pin 1 = 24Vdc
Pin 2 = Command
Pin 3 = 0Vsc Comma
Pin 4 = Pressure Feedback

3-way 2 POS NO Poppet Valve (2 pcs)

Exhaust Muffler

Exhaust Muffler

72

70

1/2" NPT on cylinder

1/2" ID hose to tee

Pneumatic Cylinder 4" bore

Pneumatic Cylinder 4" bore

FIG. 12

FIG. 13

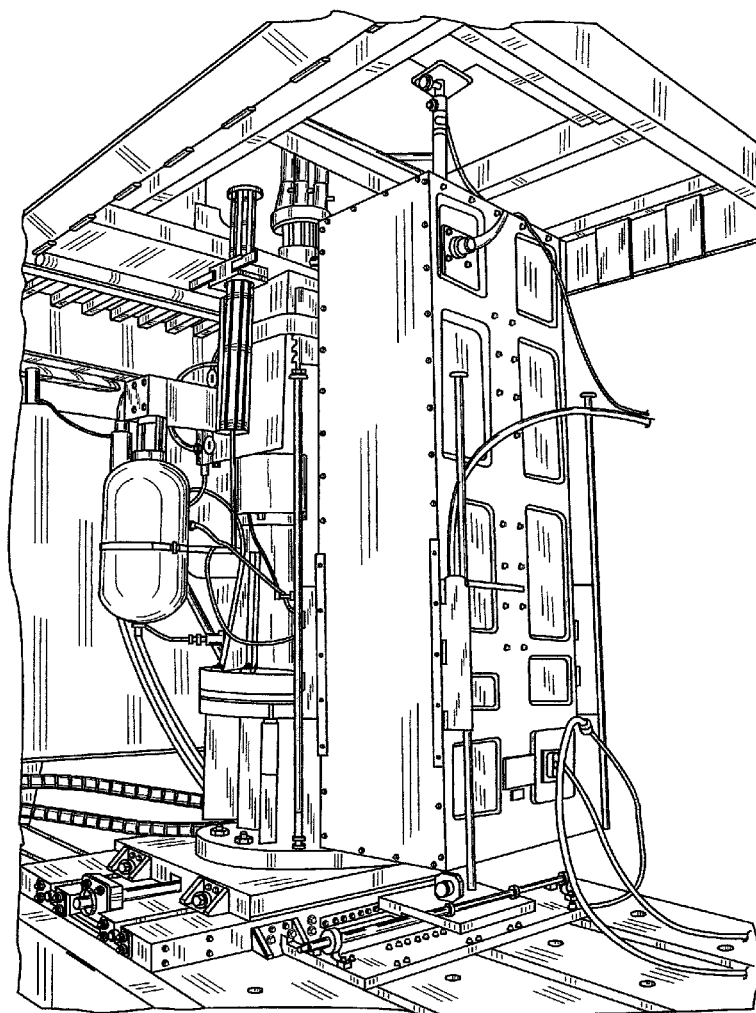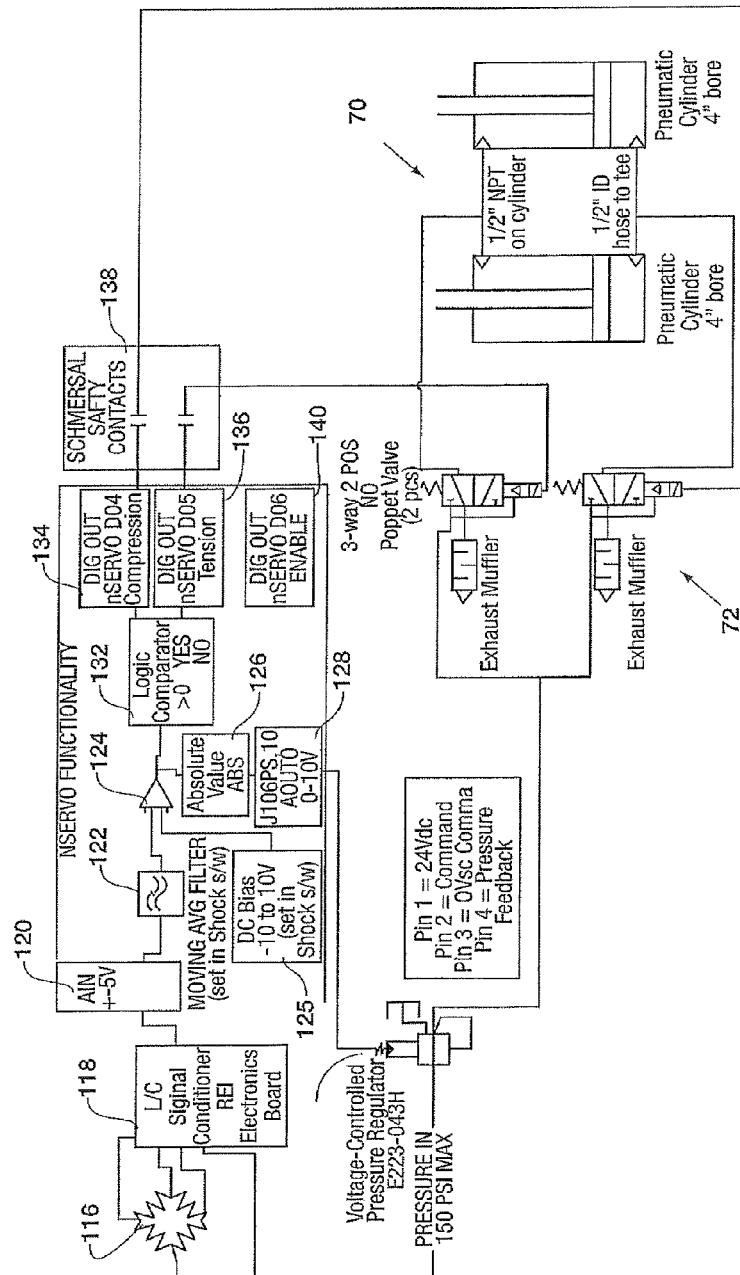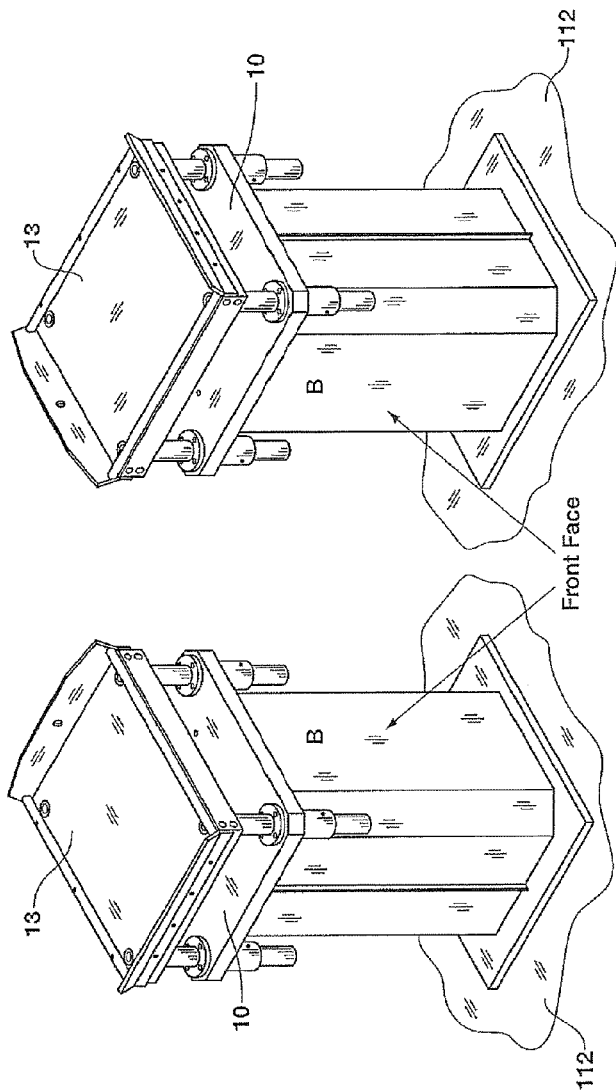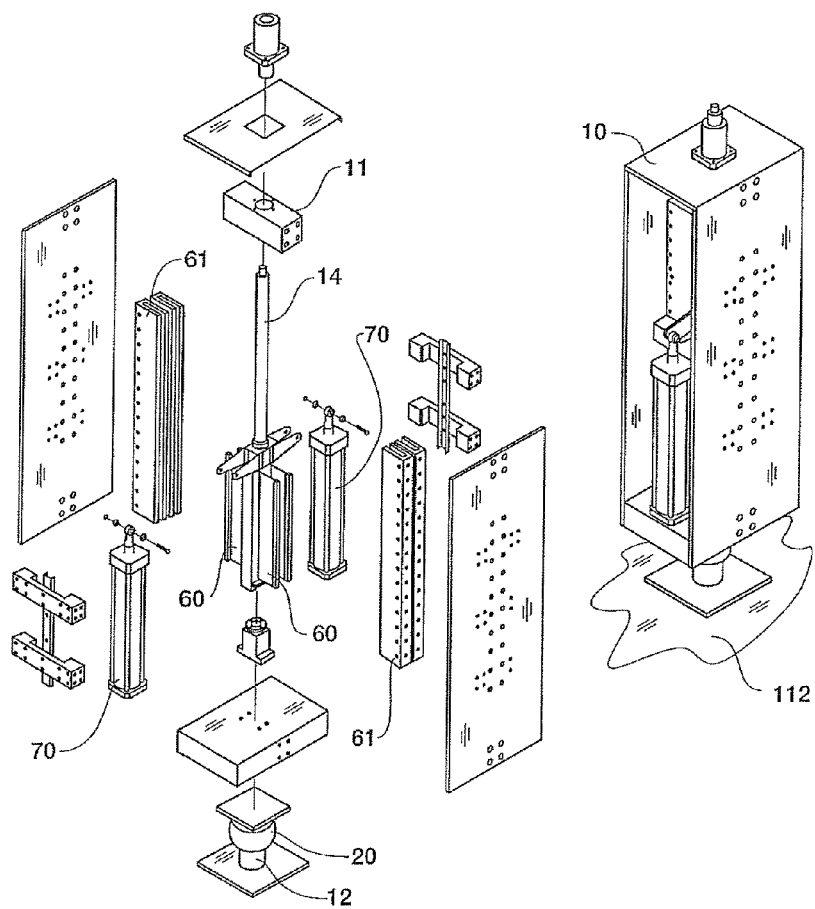# IMPARTING MOTION TO A TEST OBJECT SUCH AS A MOTOR VEHICLE IN A CONTROLLED FASHION WITH IMPROVED ACCURACY

This application is a divisional of and claims the benefit of application Ser. No. 13/280,532 filed Oct. 25, 2011, and the Oct. 25, 2010 filing date of provisional application 61/406,280 and the benefit of the Nov. 24, 2010 filing date of provisional application 61/416,825.

BACKGROUND OF THE INVENTION

The present invention deals with imparting motion to a test object such as a motor vehicle in a controlled fashion; apparatus and methods are involved.

Known vehicle shakers usually have hydraulic wheel loader actuators which sometimes have an additional piston/cylinder in parallel with the hydraulic piston/cylinder to provide a "load bias" capability. This additional parallel cylinder uses gas such as nitrogen with a simple control system to provide static loads, thereby reducing the burden from the hydraulics. Such actuators are commonly used in 4-post and 7-post vehicle shaker rigs. The industry standard for 7-post shaker rigs is to use three hydraulic body loaders with integral "compliance link" elements in addition to four hydraulic wheel loaders. Body loaders are also referred to as aeroloaders or downforce actuators. The compliance link is essentially a soft spring in series with the hydraulics. Some body loader designs use pneumatic actuation instead of hydraulics, based on a belief that the pneumatic cylinder would naturally act as a soft spring to provide performance equivalent to the industry standard, but less expensive to operate. However, such pneumatic body loader technology does not have enough control bandwidth to meet the needs of a typical 7-post or 8-post test. The industry standard hydraulic body loader solution has a higher bandwidth, but it also suffers from bandwidth limitations that are created by the presence of the "compliance link."

SUMMARY OF THE INVENTION

The present invention fulfills one or more of these needs in the art by providing an apparatus for imparting motion to a test object such as a motor vehicle in a controlled fashion including a base, at least one linear electromagnetic motor having a first end and an second end, the first end being connected to the base, at least one pneumatic cylinder and piston combination having a first end and a second end, the first end connected to the base so that the pneumatic cylinder and piston combination is generally parallel with the linear electromagnetic motor, the second ends of the linear electromagnetic motor and pneumatic cylinder and piston combination being commonly linked to a mount for the test object, and a control system for the linear electromagnetic motor and pneumatic cylinder and piston combination that drives the pneumatic cylinder and piston combination to support a substantial static load imparted to the test object, enabling the linear electromagnetic motor to provide controlled motion to the test object.

The first end of the apparatus is typically fixedly attached to an inertial ground reference.

In some embodiments both ends of the apparatus allow angular motion relative to the respective attachment points.

The apparatus may contain at least one temperature sensing means for monitoring and/or regulating the temperature of the linear electromagnetic motor. The apparatus may include at least one cooling means for cooling the linear electromagnetic motor. The cooling means include a forced air convection supplied by an external air pressure source. An automatic or a manual means of regulating the temperature of the linear electromagnetic motors may be used.

Preferably, the apparatus includes an installation means for enabling safe attachment of the mount to the test object. The installation means may restrict angular motion of the apparatus relative to the inertial ground reference. The installation means may use the second actuation means to slowly extend or retract the moving end of the apparatus to facilitate safe attachment. The installation means may include a manual lever to slowly adjust the position of the second end of the apparatus.

One preferred embodiment of the apparatus includes at least one force sensing element to provide a signal indicative of the force applied to the test object. The force sensing element may be connected in a feedback circuit to the control system to regulate the desired or specified static force imparted by the pneumatic cylinder and piston combination. The force sensing element may be connected in a feedback circuit to the control system to regulate the desired or specified dynamic force imparted by the linear electromagnetic motor.

Another preferred embodiment of the apparatus includes at least one displacement sensing element to provide a signal indicative of the linear displacement between the first end and the second end. The displacement sensing element may be connected in a feedback circuit to the control system to regulate the desired or specified static displacement. The displacement sensing element may be connected in a feedback circuit to the control system to regulate the desired or specified dynamic displacement.

Some embodiments of the apparatus may simultaneously include at least one force sensing element and at least one displacement sensing element.

In some embodiments, a plurality of the apparatuses described above are used to simultaneously impart controlled motion to multiple points of a test object. A feedback control system may be included to regulate the forces and or displacements imparted by the plurality of apparatuses.

The apparatus may include a means for disabling power to an apparatus element in the event that an unsafe condition has been determined. The apparatus may include a means for notifying the feedback control system in the event that an apparatus element enters into an unsafe condition. The apparatus may include a means for enabling power to an apparatus element such that impulsive forces are not input to the test object.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be better understood by a reading of the Detailed Description of the Examples of the Invention along with a review of the drawings, in which:

FIG. 1 is a schematic diagram of one single body loader apparatus incorporating at least one linear electromagnetic motor and at least one pneumatic cylinder and piston combination;

FIG. 2 is a block diagram of a control circuit for the body loader and/or wheel loader;

FIGS. 3-7 are block diagrams of alternate control circuits for the body loader and/or wheel loader;

FIG. 8 is a perspective side view of a quarter-car test rig incorporating linear electromagnetic motor technology as body loader actuators;

FIG. **9** is a perspective end view of a quarter-car test rig incorporating linear electromagnetic motor technology as body loader actuators;

FIG. **10** is a perspective side view of linear electromagnetic motor body loaders installed on an 8-post vehicle shaker rig;

FIG. **11** is a block diagram of a pneumatic circuit useable with the body loader and/or wheel loader;

FIG. **12** is side view of the wheel loader apparatus; and

FIG. **13** is an exploded view of the body loader apparatus.

DETAILED DESCRIPTION OF EXAMPLES OF THE INVENTION

The term "body loader" is generically used to refer to an apparatus that can impart controlled energy (forces and displacements) into a test object substantially along one axis while minimizing motion constraints along the other two orthogonal axes. Body loaders are also known as a "downforce actuators" or "aeroloaders", however, those teims are somewhat restrictive. Such devices are used in 7-post and 8-post vehicle shaker rigs to simulate aerodynamic and inertial loads applied to the chassis or body of a ground vehicle.

The term "wheel loader" is generically used to refer to an apparatus that can impart controlled energy (forces and displacements) into a test object substantially along one axis while substantially constraining motion along the other two orthogonal axes. Such devices are used in 7-post and 8-post vehicle shaker rigs to simulate road inputs to the tires or wheel hubs of a ground vehicle.

FIG. **1** is a schematic diagram of one single body loader apparatus based on Electro-Magnetic Actuation (EMA) technology. A rigid housing **10** provides a base of support for the moving member **14** with an integral shaft. The moving member is constrained to allow relative linear motion provided by bearings **11** attached to the rigid housing **10**. To maximize body loader performance, it is necessary for the moving member **14** to be as lightweight as possible. The base of the body loader, which is also called the "stationary" or first end, is fixedly attached to an inertial ground reference through stationary attachment means **12**. For the body loader embodiment, the stationary attachment means **12** must allow angular motion of the rigid housing **10** relative to the inertial ground reference. Also for the body loader embodiment, the moving end of the body loader is fixedly attached to the test object through moving attachment means **13**. Moving attachment means **13** must allow angular motion of the moving member **14** relative to the test object. Both attachment means **12** and **13** must have a very limited "rattlespace" such as what can be achieved with a high compression ball joint.

As seen in FIG. **1**, the apparatus includes an installation support means **15** for restricting angular motion of the rigid housing **10** relative to the inertial ground reference during the installation process while the moving attachment **13** is being connected to the test object. Preferably, the installation support means **15** allows some degree of manual adjustment to enable the rigid housing **10** to be positioned over a range of possible angles relative to the inertial ground reference.

FIG. **1** shows that the apparatus contains at least one linear electromagnetic motor to impart controlled dynamic and static actuation forces to the test object. The linear electromagnetic motor is made up of at least one coil element **60** fixedly attached to the moving member **14**, and at least one U-shaped permanent magnet track **61** fixedly attached to the rigid housing **10**. Alternative linear electro-

magnetic motor designs may use electromagnets to replace or supplement permanent magnets. At least one power amplifier **63** delivers controlled current to the at least one coil element **60** through the at least one wiring harness **62** in response to a command voltage **64**. Alternative power amplifier designs may deliver controlled voltage to the at least one coil element **60**.

The apparatus of FIG. **1** contains at least one secondary actuation means **70** in parallel with the linear electromagnetic motor to impart controlled static forces to the test object. The at least one secondary actuation means **70** must be capable of generating static loads, but it must also be relatively compliant to accommodate dynamic motions. The preferred at least one secondary actuation means **70** is a pneumatic cylinder and piston assembly. The base end of the at least one secondary actuation means **70** is fixedly attached to the rigid housing **10**, and the moving end of the at least one secondary actuation means **70** is fixedly attached to the moving member **14** at attachment **71**. A controllable valve **72** is mounted on or near the rigid housing **10**. Controllable valve **72** is supplied with pressurized gas through supply line **74** from an external pressure source **73**. The pneumatic valve **72** is responsive to control input **75** from a control system and/or from manual input means **76** mounted on or near the rigid housing. Manual input means **76** provides a means for slowly adjusting the position of the moving attachment means **13** so that it may safely be connected to the test object. The safe attachment is aided by the use of a proportional valve and poppet to allow control of the pneumatic cylinder while manipulating it manually.

FIG. **11** shows a schematic diagram of a control circuit for the pneumatics. The load cell **116** outputs a signal to the load cell signal conditioner **188** that raises the voltage output from the millivolt range to +/−5 volts. That signal is applied to a moving average filter **122** and its output is applied to a comparator **124** that also receives a dc bias voltage from voltage source **125**. The output of the comparator is a binary signal indicating if the load is positive or negative. That signal is applied to a logic comparator **132** that outputs a signal to DIG OUT nServo **134** if compression is needed and to DIG OUT nServo **136** if tension is needed. That selection is applied to an optional status display **140** and also through safety contacts **138** to the valves **72** for the pressurized air supply that control the supply of pressurized air to the pneumatic cylinder **70**. This circuit branch thus controls the direction of pressurized air application

The output of the comparator **124** is also applied to a component **126** that takes the signal's absolute value and applies it through pressure control component **128** to get a force magnitude signal that is applied to a voltage controlled pressure regulator **130** to affect the pressure applied though the valves **72** to the cylinder **70**. This circuit branch enables the magnitude of the pressure application to be controlled.

The apparatus typically has at least one cooling means **77** for cooling the at least one coil element **60**. An example of a cooling means is forced convection using a gallery, header or air knife which directs a sheet of air through the air gap between the at least one coil element **60** and the permanent magnet track **61**. Water, or some other fluid, may be used as an alternative at least one cooling means.

Preferably, the apparatus contains at least one temperature sensing means **50** for monitoring and/or regulating the temperature of the at least one coil element **60**. A temperature sensor wiring harness **51** transmits an electrical signal to an external signal conditioning unit **52** which generates a coil temperature signal **53** indicative of the actual coil element temperature.

As seen in FIG. **1**, one preferred embodiment of the apparatus includes at least one force sensing means **30** to measure the dynamic and static force applied to the test object. In this embodiment, the apparatus is used to create controlled forces imparted to the test object, and the at least one force sensing means **30** is preferably located as close as possible to the moving attachment means **13**. A force sensing wiring harness **31** transmits an electrical signal to a signal conditioning unit **32** which generates a transmitted force signal **33** indicative of the actual force transmitted through the at least one force sensing means **30**.

In a second embodiment of the apparatus, a secondary force sensing means **20** is located near the stationary attachment means **12**. The secondary force sensing means **20** also measures the static and dynamic force applied to the test object; however, when the apparatus is vertically oriented, the secondary force sensing means **20** also measures the static weight of the stationary portion of the apparatus. A secondary force sensing wiring harness **21** transmits an electrical signal to a signal conditioning unit **22** which generates a secondary transmitted force signal **23** indicative of the actual force transmitted through the secondary force sensing means **20**.

With respect to FIG. **1**, one preferred embodiment of this apparatus includes a relative displacement sensing means **40** to measure the displacement between the rigid housing **10** and the moving member **14**. A relative displacement sensing wiring harness **41** transmits an electrical signal to a signal conditioning unit **42** which generates a relative displacement signal **43** indicative of the actual displacement between the rigid housing **10** and the moving member **14**. In one embodiment of the apparatus, the relative displacement signal **43** can be used in a feedback control system to regulate the position of the movable member **14**. In this particular embodiment of the apparatus, the transmitted force signal **33** is not used in a feedback control system. The relative displacement signal **43** can also be used as a measure of the displacement of the test object relative to the inertial ground reference. In a preferred embodiment of this invention, a plurality of body loader apparatus elements are attached to a test object to simultaneously impart controlled energy at multiple points.

The wheel loader apparatus (see FIG. **13**) is a modified version of the body loader apparatus described in the previous section. For the wheel loader apparatus embodiment, the rigid housing **10** is fixedly attached to the inertial reference frame **112** in such a way as to disallow relative angular motion between the wheel loader and the inertial reference frame.

In the wheel loader apparatus embodiment seen in FIG. **12**, the moving attachment **13** is a flat plate oriented perpendicular to the axis of motion. The moving attachment **13** is fixedly attached to the at least one load cell **30** which in turn is fixedly attached to the moving member **14** such that relative angular motion between the moving attachment **13** and the moving member **14** is disallowed. The flat plate moving attachment **13** is typically referred to as a "wheel-pan" in 4-post, 7-post, and 8-post rigs.

In the wheel loader apparatus embodiment, an acceleration sensing means (not shown in FIG. **1**) is fixedly attached to the moving attachment **13**. A signal indicative of the acceleration is used to compensate for the inertial forces measured by the at least one force sensing means **30** and caused by motion of the mass of the moving attachment **13**. This compensation enables a more accurate measurement of the actual force transmitted to the test object. This compen-

sation is only required when the mass of the moving attachment **13** is significant enough to cause errors in the transmitted force signal **33**.

With respect to FIG. **2**, the transmitted force signal **33** from the apparatus is compared to a specified force signal **81** through summing element **82** to produce a first force error **83**. The first force error **83** is input to a High-Bandwidth Force Feedback Control operation **80** which generates a command voltage **64** to drive the at least one linear electromagnetic motor within an individual body loader or wheel loader apparatus. The High-Bandwidth Force Feedback Control operation **80** is preferably an integral control action with additional dynamic compensation terms to shape the closed-loop response. Because there is a substantially linear relationship between the command voltage **64** and the transmitted force signal **33**, the open-loop dynamics are relatively simple which allows the use of a correspondingly simple High-Bandwidth Force Feedback Control operation **80**. The method implementing the circuit of FIG. **2** does not utilize the at least one secondary actuator means **70** to provide static load assist to the at least one linear electromagnetic motor. Although this operational mode increases the likelihood of thermal problems, it still has utility. In another embodiment of FIG. **2**, the pneumatic valve associated with the secondary actuator means may be controlled with a manually determined setpoint.

FIG. **3**, FIG. **4**, and FIG. **5** represent alternate methods for imparting controlled force which do utilize the at least one secondary actuator means **70**.

In addition to the High-Bandwidth Force Feedback Control operation **80**, the method described by FIG. **3** compares the specified force signal **81** with the secondary transmitted force signal **23** through summing element **82** to produce a second force error **84**. The second force error **84** is input to a Low-Bandwidth Force Feedback Control operation **85** which generates a control input **75** to drive the at least one secondary actuation means **70** within an individual body loader or wheel loader apparatus. The Low-Bandwidth Force Feedback Control operation **85** has a restricted bandwidth that limits its operation to control only static loads.

In addition to the High-Bandwidth Force Feedback Control operation **80**, the method described by FIG. **4** uses the first force error **83** directly as input to a Low-Bandwidth Force Feedback Control operation **85** which generates a control input **75** to drive the at least one secondary actuation means **70** within an individual body loader or wheel loader apparatus.

A preferred method for imparting controlled force is shown in FIG. **5**. In addition to the High-Bandwidth Force Feedback Control operation **80**, the method described by FIG. **5** uses the command voltage **64** with a command force estimation operation **87** to generate an estimate of the specified force **88**. This approximation provides a significant implementation benefit and is justified because of the substantially linear relationship between the command voltage **64** and the transmitted force signal **33**. The command force estimation operation **87** utilizes knowledge of the motor constant, which relates applied current to generated force, and the gain of the power amplifier **63**. The estimate of the specified force **88** is then compared to the secondary transmitted force signal **23** through summing element **82** to produce a third force error **86**. The third force error **86** is then input to a Low-Bandwidth Force Feedback Control operation **85** which generates a control input **75** to drive the at least one secondary actuation means **70** within an individual body loader or wheel loader apparatus.

In addition to the High-Bandwidth Force Feedback Control operation 80, another preferred method described by FIG. 5 also uses the command voltage 64 with a command force estimation operation 87 to generate an estimate of the specified force 88; however, the estimate of the specified force 88 is then compared to a zero setpoint value (not shown in FIG. 5) through summing element 82 to produce a fourth force error 86. The fourth force error 86 is then input to a Low-Bandwidth Force Feedback Control operation 85 which generates a control input 75 to drive the at least one secondary actuation means 70 within an individual body loader or wheel loader apparatus. This particular embodiment drives the command voltage 64 toward zero, thus shifting the static load to the secondary actuation means 70.

With respect to FIG. 6, the relative displacement signal 43 from the apparatus is compared to a specified displacement signal 91 through summing element 92 to produce a first displacement error 93. The first displacement error 93 is input to a High-Bandwidth Position Feedback Control operation 90 which generates a command voltage 64 to drive the at least one linear electromagnetic motor within an individual body loader or wheel loader apparatus. The High-Bandwidth Position Feedback Control operation 90 is preferably an integral control action with additional dynamic compensation terms to shape the closed-loop response. The method described by FIG. 6 does not utilize the at least one secondary actuator means 70 to provide static load assist to the at least one linear electromagnetic motor. In another embodiment of FIG. 6, the pneumatic valve associated with the secondary actuator means may be controlled with a manually determined setpoint.

The preferred method for imparting controlled displacement is shown in FIG. 7. In addition to the High-Bandwidth Position Feedback Control operation 90, the method described by FIG. 7 uses the command voltage 64 with a command force estimation operation 87 to generate an estimate of the specified force 88. This approximation provides a significant implementation benefit and is justified because of the substantially linear relationship between the command voltage 64 and the transmitted force signal 33. The command force estimation operation 87 utilizes knowledge of the motor constant, which relates applied current to generated force, and the gain of power amplifier 63. The estimate of the specified force 88 is then compared to the secondary transmitted force signal 23 through summing element 82 to produce a third force error 86. The third force error 86 is then input to a Low-Bandwidth Force Feedback Control operation 85 which generates a control input 75 to drive the at least one secondary actuation means 70 within an individual body loader or wheel loader apparatus.

In addition to the High-Bandwidth Position Feedback Control operation 80, another method described by FIG. 7 also uses the command voltage 64 with a command force estimation operation 87 to generate an estimate of the specified force 88; however, the estimate of the specified force 88 is then compared to a zero setpoint value (not shown in FIG. 7) through summing element 82 to produce a fourth force error 86. The fourth force error 86 is then input to a Low-Bandwidth Force Feedback Control operation 85 which generates a control input 75 to drive the at least one secondary actuation means 70 within an individual body loader or wheel loader apparatus. This particular embodiment drives the command voltage 64 toward zero, thus shifting the static load to the secondary actuation means 70.

Linear electromagnetic motor coils are subject to relatively rapid resistive heating whenever a sustained DC current is applied, such as when specified to apply a static

force. One method for regulating the temperature of the linear electromagnetic motor coil is to enable, disable, or otherwise control the at least one cooling means 77 in response to the coil temperature signal 53. The decision to enable, disable, or otherwise control the at least one cooling means 77 can be performed by an automatic controller or by a human operator monitoring the coil temperature signal 53. Another method for regulating the temperature of the linear electromagnetic motor coil is to disable or completely shut down the associated at least one power amplifier 63 in response to the coil temperature signal 53. This approach is intended to be a failsafe operation to prevent overheating.

Another method for regulating the temperature of the linear electromagnetic motor coil is to enable the at least one secondary actuation means 70 in response to the coil temperature signal 53. This approach allows the at least one secondary actuation means 70 to apply a significant portion of the static load to the test object, thus relieving the linear electromagnetic motor from this requirement.

One method for insuring safe operation is to disable or completely shut down all power amplifiers 63 in the event that an unsafe condition has been identified. Unsafe events may include, but are not limited to at least one of: displacement out of range, velocity out of range, acceleration out of range, force out of range, and temperature out of range. The overall control system needs to be able to shut down the apparatus and the apparatus needs to be able to shut down the overall control system.

A method is required for preventing impulsive startup conditions when the apparatus is used to impart a controlled force or when the apparatus is used to impart a controlled displacement.

One method for preventing impulsive startup conditions is to first set the initial specified force signal 81 (or the initial specified displacement signal 91) to be identical to the transmitted force signal 33 (or the relative displacement signal 43). This will cause the initial first force error 83 (or the initial first displacement error 93) to be zero, thereby causing the high bandwidth feedback controller output to be zero. Next, the power amplifiers 63 are enabled, and finally, the initial specified force signal 81 (or the initial specified displacement signal 91) is linearly ramped to the actual desired or specified force signal 81 (or the actual desired or specified displacement signal 91).

An alternative method is to hold the initial first force error 83 (or the initial first displacement error 93) to be zero, then enable the power amplifiers 63, and finally limit the rate at which the first force error 83 (or the first displacement error 93) is allowed to reach its initial steady-state level.

In the case where the mass of the moving attachment 13 is significant, as in a wheelpan for a wheel loader, inertial compensation is required to obtain a more accurate transmitted force. In this case, the transmitted force signal 33 contains two components. The first component is the actual force transmitted to the test object. The second component is an inertial force caused by accelerating the mass of the moving attachment 13. This second component is the term that distorts the transmitted force signal 33, and must be removed. Mathematically, this relationship can be expressed using Newton's second law of motion as:

$$F\text{meas} = F\text{transmitted} + (M\text{attachment} \times A\text{attachment}) \qquad (1)$$

Where Fmeas is the Transmitted Force signal 33 as measured by Force Sensing means 30

Ftransmitted is the Actual force transmitted to the test object

Mattachment is the Mass of the moving attachment **13** and

Aattachment is the Acceleration of the moving attachment **13**

Notice that if the mass of the moving attachment **13** is relatively small or zero, the transmitted force signal **33** is equal to the actual force transmitted to the test object. For a variety of practical reasons including higher order vibrational modes of the mass and dynamic filters applied to the measured force and acceleration signals, the inertial term in equation (1) is often not an accurate representation of a real dynamic system implementation. The preferred method for inertial compensation of transmitted force signal begins with the step of removing the test object from the apparatus thereby causing Ftransmitted to be zero. The next step is to command the apparatus with an excitation signal that covers the operating frequency range of the testing.

The excitation signal, which would typically be a specified displacement signal **91**, can be a random noise signal or a swept sine signal. During the excitation step, both the transmitted force signal **33** and the acceleration of the moving attachment **13** are recorded. The next step in the inertial compensation method is to construct a dynamic filter to represent the transfer function between the transmitted force signal **33** as a response, and the acceleration of the moving attachment **13** as an excitation. This transfer function can be expressed by the complex frequency domain representation of equation (2):

$$m(f) = \frac{F transmitted\ (f)}{aattachment\ (f)} \qquad (2)$$

where f represents the frequency. There are many available well-known techniques for constructing a suitable dynamic filter from the input-output data. One preferred approach is to compute a complex frequency response function in the frequency domain and then fit the resulting complex data with an infinite impulse response filter. The infinite impulse response filter will become the required dynamic filter. When the measured acceleration data is input to the infinite impulse response filter, the output of the filter is a more accurate prediction of the inertial force which can then be subtracted from the transmitted force signal **33** to generate a more accurate estimate of the actual force transmitted to the test object.

Another preferred approach is to design a finite impulse response filter using the measured force and acceleration data. There are many available well-known techniques for determining the coefficients of a finite impulse response filter to represent the dynamics between the input measured acceleration data and the output measured force data. Such techniques include gradient-descent search algorithms such as Least-Mean-Squares, or conventional optimization algorithms.

Embodiments of the invention described by this disclosure also include a method for incorporating a plurality of apparatus elements. There are many possible combinations such as: a 2-post quarter car rig with one wheel loader and one body loader; a 4-post vehicle shaker rig with four wheel loaders; a 7-post vehicle shaker rig with four wheel loaders and three body loaders; and an 8-post vehicle shaker rig with four wheel loaders and four body loaders.

FIG. **8** and FIG. **9** are photographs of a fully functional quarter-car test rig incorporating linear electromagnetic motor technology as body loader actuators with a hydraulic

wheel loader. The quarter-car test rig utilizes two separate linear electromagnetic motors, one on each side of the sprung mass plate which is constrained to move vertically on two precision bearing rails. The left hand side of FIG. **9** shows one linear electromagnetic motor attached to the left side of the quarter-car. The U-shaped permanent magnet track (silver object) is attached to the rigid frame, and the coil element is attached to the moving sprung mass plate. FIG. **9** also shows a linear encoder that is used to sense the relative displacement. The quarter car rig in FIG. **8** and FIG. **9** does not include a secondary actuation means **70** as described above.

FIG. **10** is a photograph of a body loader incorporating linear electromagnetic motors and a pneumatic cylinder and piston assembly installed on an 8-post vehicle shaker rig. Only one body loader is clearly visible in this photograph (center of image) although four are actually installed in the depicted 8-post rig. A hydraulic wheel loader is also shown in FIG. **10** behind the body loader. Working from the top to the bottom of the body loader in FIG. **10**, the photograph clearly shows the moving attachment means **13**, the at least one force sensing means **30**, the shaft of the moving member **14**, the rigid housing **10**, the installation support means **15**, and the manual input means **76**.

The EMA series, in its basic configuration, is very efficient at reproducing dynamic motions. With frequency response well above many servo hydraulic systems, the EMA is well suited for applications that need high dynamic force along with high velocities or accelerations. But for applications that also require supporting a static mean load, such as vibration work on larger test objects or testing many suspension components, vehicle subassemblies, or even entire vehicles, the EMA can be combined with a pneumatic preload system to enhance its capabilities. This option is called Static Air Assist (SAA).

The SAA system consists of relatively low tech devices, with low frequency response, by design. It is capable of supporting higher static loads without affecting the dynamic performance of the linear electromagnetic motors. SAA also consumes very little energy, as it essentially only uses energy upon system startup. Once energized, the pneumatic pressure is constant and doesn't require additional energy unless test parameters are changed. When de-energized, the system gradually releases the stored energy, resulting in a controlled shutdown.

The SAA option also takes advantage of readily available shop air at 80 psi or less. In the event shop air is not available, or excess capacity does not exist, a standard air compressor can be added.

Until now, the excellent performance of the EMA linear electromagnetic motors have been limited to use in specific testing applications. Now, with the addition of the Static Air Assist, the EMA series can be applied to a wider testing market, which require significant mean loads relative to the dynamic performance.

The Static Air Assist option can be added to existing systems, and in no way diminishes the dynamic performance of the EMA linear electromagnetic motors. In fact, as the SAA eliminates mean loads, more EMA performance is available for use in dynamic motion, thereby enhancing existing performance.

This combination of functionality provides the test engineer with an efficient, clean, compact, and high response system.

Certain modifications and improvements will occur to those skilled in the art upon reading the foregoing description. It should be understood that all such modifications and

improvements have been omitted for the sake of conciseness and readability, but are properly within the scope of the following claims.

What is claimed is:

1. A method of improving the accuracy of a measured dynamic transmitted force in an apparatus which imparts motion to a test object in a controlled fashion by applying a force to the test object, comprising the steps of:

measuring acceleration of a movable test object and generating a signal indicative of the measured acceleration of the movable test object and transmitting the signal indicative of the acceleration of the movable test object;

filtering said signal indicative of the measured acceleration of the movable test object in a dynamic filter tuned to dynamic characteristics of the apparatus to generate a dynamic compensation force signal;

adding the dynamic compensation force signal to a signal indicative of the force applied to the test object to generate a compensated dynamic transmitted force signal.

2. The method as claimed in claim 1, wherein said dynamic filter is a digital finite impulse response filter.

3. The method as claimed in claim 2 wherein the digital finite impulse response filter represents dynamics between an input measured acceleration data and output measured force data using a gradient-descent search algorithm.

4. The method as claimed in claim 1 wherein the dynamic filter is a moving average filter.

5. The method as claimed in claim 1 wherein the dynamic filter includes a transfer function between the force applied to the test object as a response, and the measured acceleration of the test object as an excitation.

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